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[54] WINGTIP MOUNTED,  
COUNTER-ROTATING PROPROTOR FOR  
TILTWING AIRCRAFT

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B64C 27/22; B64C 27/52

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244/56; 244/66; 244/69

[58] Field of Search ..... 244/6, 7 C, 7 R, 12.4,  
244/17.23, 56, 66, 69

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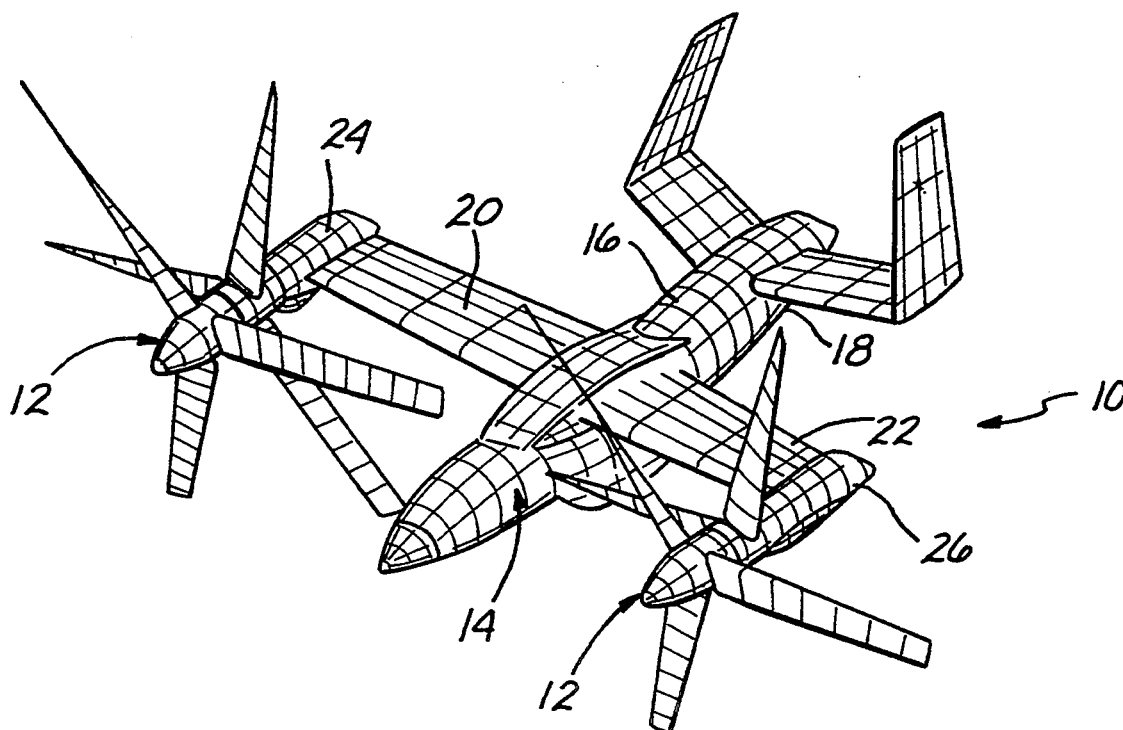
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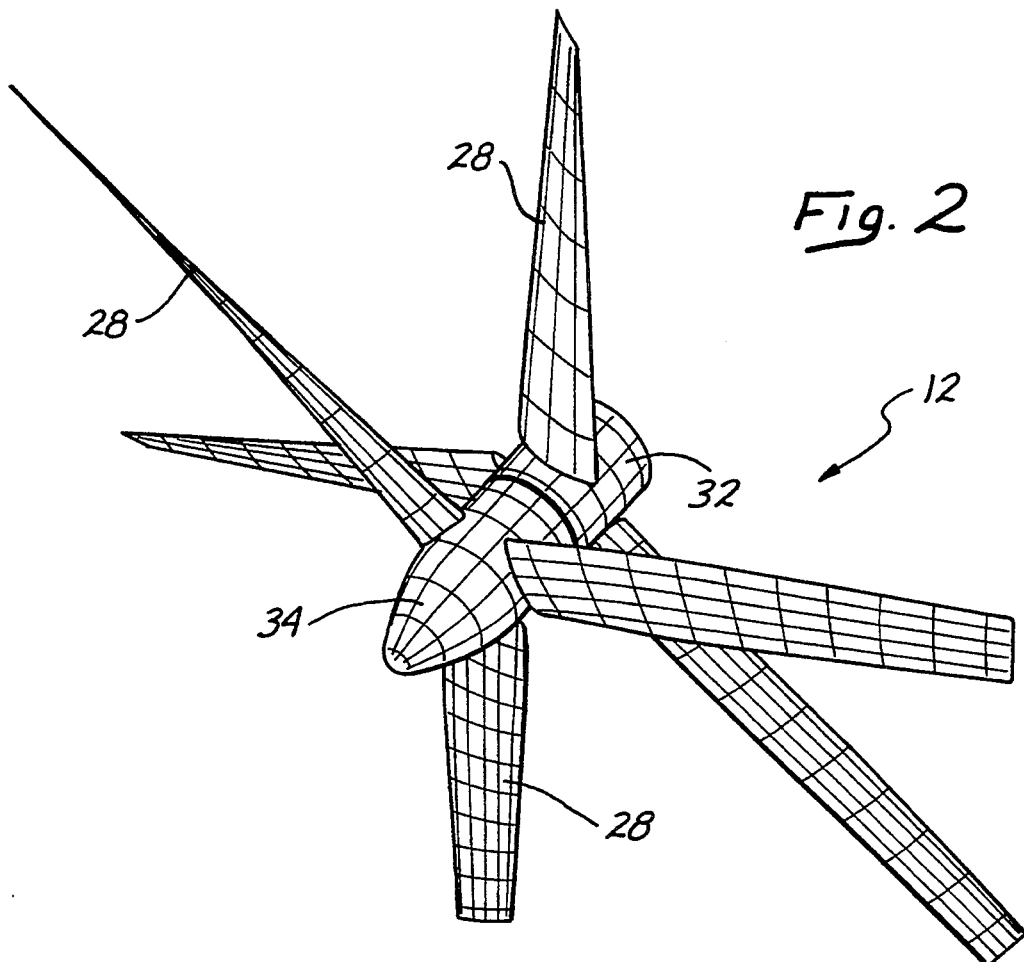
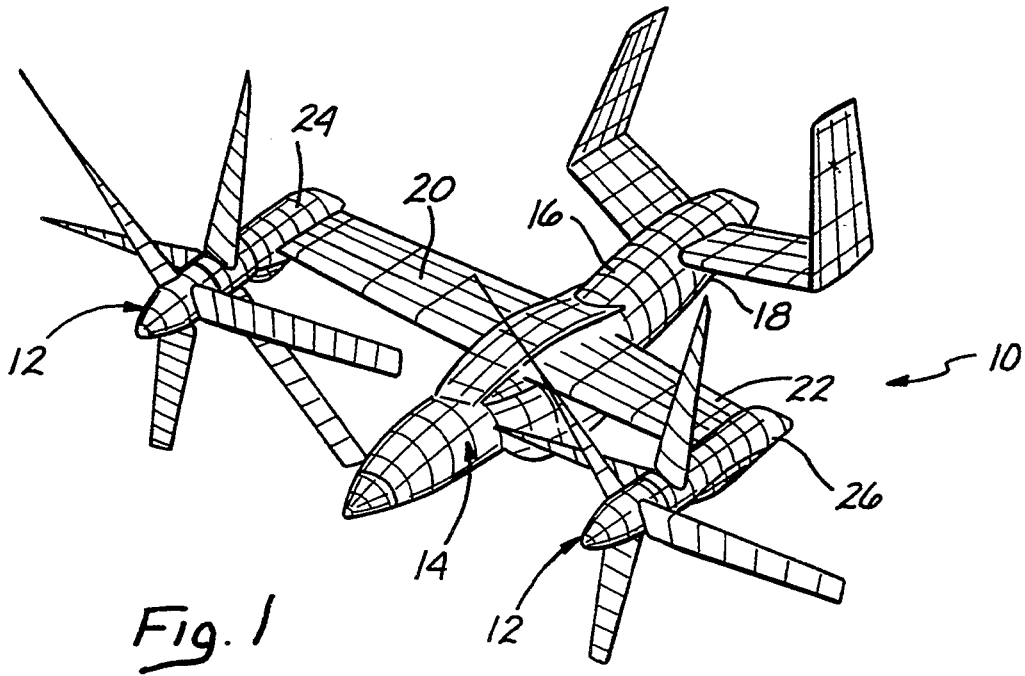
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## [57] ABSTRACT

A tiltwing aircraft, capable of in-flight conversion between a hover and forward cruise mode, employs a counter-rotating propotor arrangement which permits a significantly increased cruise efficiency without sacrificing either the size of the conversion envelope or the wing efficiency. A benefit in hover is also provided because of the lower effective disk loading for the counter-rotating propotor, as opposed to a single rotation propotor of the same diameter. At least one propotor is provided on each wing section, preferably mounted on the wingtip, with each propotor having two counter-rotating blade rows. Each blade row has a plurality of blades which are relatively stiff-in-plane and are mounted such that cyclic pitch adjustments may be made for hover control during flight.

8 Claims, 2 Drawing Sheets





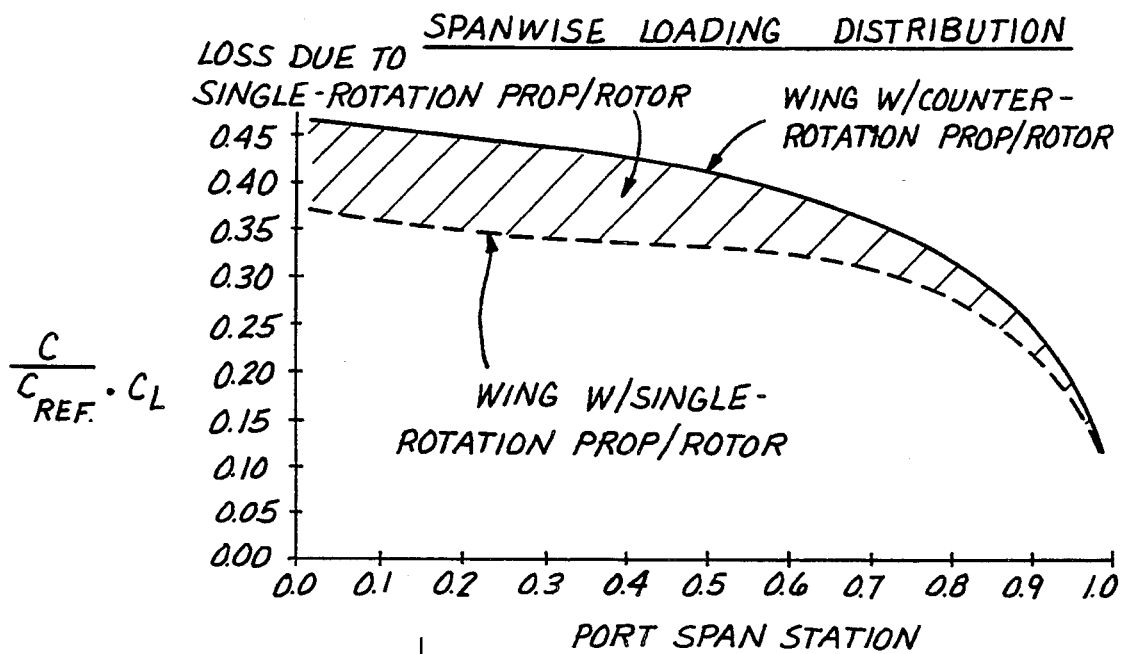


Fig. 3

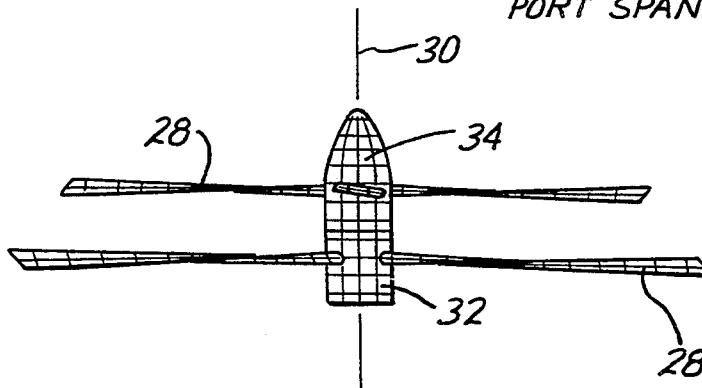


Fig. 4

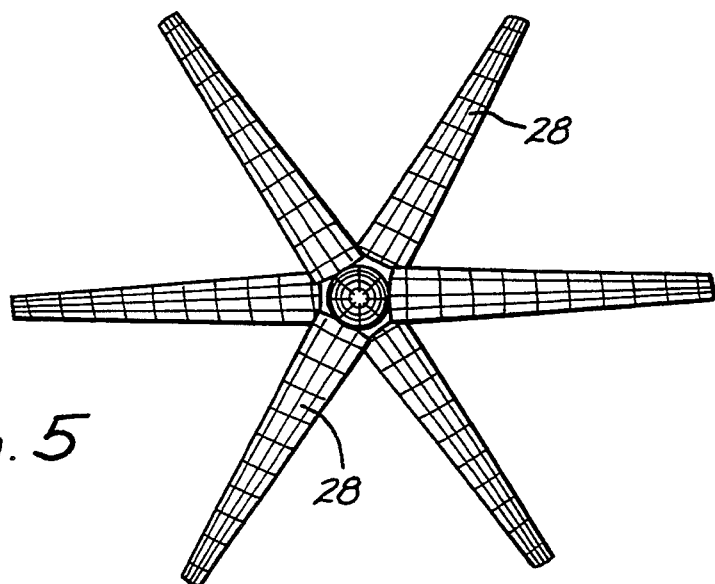


Fig. 5

## WINGTIP MOUNTED, COUNTER-ROTATING PROPROTOR FOR TILTWING AIRCRAFT

The invention described herein was made in the performance of work under NASA Contract No. NAS2-13070 and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958 (42 U.S.C. 2457).

### BACKGROUND OF THE INVENTION

This invention relates to aircraft, and more particularly to a new concept of a counter-rotating propotor designed for wingtip mounting on tiltwing aircraft.

Tiltwing aircraft are designed to tilt their wing from a horizontal position in cruise to a vertical position in hover. They operate like a helicopter with the wing in the vertical position. For high speed forward flight, the wing tilts to the horizontal position and operates in a manner similar to that of a standard turboprop airplane. To successfully convert the aircraft from hover to cruise (conversion) or from cruise to hover (reconversion) the wing must operate over a wide range of angles of attack without stalling. The propulsors (usually propellers or a hybrid propeller/rotor combination called a propotor, which provides the attributes of a propeller when in the level flight (cruise) position and the attributes of a helicopter rotor when in the vertical (hover) position) have a strong impact on the wing's angle of attack range since they (1) increase the velocity over the wing (this is beneficial), (2) deflect the flow over the wing (this too is beneficial), and (3) in single rotation propulsors impart a swirl component to the flow over the wing. This third feature may be either beneficial or detrimental, depending upon the direction of the swirl component. In order to reduce the power requirements of tiltwing aircraft, thereby making them more efficient and more attractive with respect to conventional single-mission type aircraft, it is desirable to move the propotors outboard to the wingtip, so that larger diameter (lower disk loading) propotors may be used. This has a negative impact on the aircraft's conversion envelope (the combination of altitude, descent rate, and power setting) however, because reducing the disk loading also reduces the velocity increase over the wing and the deflection angle of the propotor slipstream.

For low disk loading, single-rotation, wingtip-mounted propotors, the swirl imparted to the flow has a significant impact on a tiltwing aircraft's conversion envelope and cruise performance. If the propotor is turned in a direction opposite to the wingtip vortex, a wing efficiency benefit is realized. However, during conversion, turning the propotor in this direction causes a swirl component that increases the wing's angle of attack, causing the wing to stall at a lower incidence angle. This reduces the conversion envelope. Contrarily, if the propotor is turned in the same direction as the wingtip vortex, the conversion envelope is increased but the wing efficiency is decreased. Thus, the designer is faced with a paradox of either decreasing the conversion envelope or decreasing the wing efficiency.

What is needed, therefore, is a new approach which does not force a tradeoff between the size of the conversion envelope and the wing efficiency, while permitting an increased cruise (or propulsor) efficiency.

### SUMMARY OF THE INVENTION

This invention solves the problem outlined above by providing a new propotor arrangement which permits a significantly increased cruise efficiency without sacrificing either the size of the conversion envelope or the wing efficiency. There is also a benefit in hover. The effective disk loading for the counter-rotating propotor is lower, thus reducing the induced power over a single propotor of the same diameter, producing the same thrust. As a result, with this innovation, the cruise performance of a tiltwing aircraft is greatly improved over comparable single-rotation propotors and the hover performance is significantly improved over typical propeller driven tiltwings. This greater performance is sufficient to make the tiltwing design competitive for certain missions because of its greater versatility.

The invention comprises an aircraft capable of in-flight conversion between a hover and a forward cruise mode which comprises a fuselage having a starboard side and a port side. A wing section extends from each of the starboard and port sides, each wing section being fixed in both the hover mode and the forward cruise mode. At least one propotor is mounted on each of the starboard and port wing sections. Each propotor has two blade rows positioned one behind the other along a common rotational axis, with each blade row having a plurality of blades which are relatively stiff-in-plane (as compared to soft-in-plane helicopter rotors) and are mounted such that cyclic pitch adjustments may be made for hover control during flight. The two blade rows are counter-rotating.

Preferably, the aircraft is of the tiltwing type, with the wing sections tilting, in a conversion mode, from a vertical position in the hover mode to a horizontal position in the forward cruise mode, and conversely tilting, in a reconversion mode, from a horizontal position in the forward cruise mode to a vertical position in the hover mode. Each propotor consists of two, preferably gimbaled rotor hubs, with one blade row being mounted on each hub. These hubs are configured to allow full cyclic pitch adjustment of each blade.

The above mentioned and other objects and features of this invention and the manner of attaining them will become apparent, and the invention itself will be best understood, by reference to the following description taken in conjunction with the accompanying illustrative drawings.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an isometric perspective view of a tiltwing aircraft incorporating the counter-rotating propotors of the invention;

FIG. 2 is an enlarged isometric view of one of the counter-rotating propotors shown in FIG. 1;

FIG. 3 is a graph depicting the incremental change in lift across the wingspan in cruise, comparing a wing having a single rotation propotor to an identical wing having a counter-rotating propotor;

FIG. 4 is a side view of the counter-rotating propotor shown in FIG. 2; and

FIG. 5 is a top view of the counter-rotating propotor shown in FIG. 2.

### DETAILED DESCRIPTION OF THE DRAWINGS

Referring now to FIG. 1, there is shown a VSTOL (Vertical Short TakeOff and Landing) tiltwing aircraft

10 which includes a plurality of counter-rotating propellers 12, a fuselage 14 which has a starboard side 16 and a port side 18, and wing sections 20 and 22, extending from each of the fuselage starboard and port sides 16, 18, respectively. In the preferred embodiment, one counter-rotating propeller 12 is mounted on the tip 24, 26 of each wing section 20, 22. Mounting the propeller 12 on the tip of the wing section, or as closely thereto as possible, is advantageous since it allows larger diameter (lower disk loading) rotors to be used, without the risk of impacting the fuselage with the rotating rotor blades. Of course, it is within the scope of the invention to mount the propeller anywhere along the length of the wing section 20, 22, as well as to employ two or more propellers 12 on each wing section. In the case where more than one propeller is mounted on each wing section 20, 22, it will generally be advantageous to mount one on each wing tip 24, 26, with the others on each wing section 20, 22 being mounted as closely to the wingtip as possible, though they may in fact be mounted anywhere along the length of each wing section, depending upon various design considerations.

Now viewing FIGS. 2, 4, and 5, which show in greater detail a representative low disk loading, counter-rotating propeller 12, it can be seen that the propeller 12 comprises two rows of blades 28 mounted one behind the other along axis 30 and rotating counter to one another. In one preferred embodiment, three blades 28 are employed in each blade row, but any number of blades could be used. The blades 28 are constructed in a manner similar to a helicopter blade, but, unlike a typical helicopter blade, are stiff-in-plane as opposed to soft-in-plane. The blades' airfoils, planform, and twist distribution are aerodynamically optimized to provide the best compromise between cruise and hover performance. The blades are mounted on two rotor hubs 32, 34 so that full cyclic pitch control is provided. Cyclic control of the rotors provides control of the aircraft during helicopter flight. This locks out in aircraft mode, with control accomplished using conventional airplane control surfaces. Various types of rotor hubs may be employed, although a gimbaled hub design, because of its lack of complexity, is preferred. The design of the blades 28 themselves is generally based upon the known design of the single rotation propellers used on the Bell-Boeing V-22 Osprey tiltrotor aircraft currently in development for the U.S. Department of Defense, though of course other designs could be used. In any event, the blades 28 would need to be specifically designed for adaptation to the performance envelope required in a particular aircraft, this design procedure being within the purview of one of ordinary skill in the art.

As noted above, single-rotation propellers for fixed wing aircraft, wherein the propeller is capable of full cyclic pitch adjustments, as opposed to an ordinary propeller which does not provide for cyclic pitch adjustment, are known in the prior art. However, the inventors have discovered that their novel counter-rotating propeller arrangement provides for unexpectedly improved results when employed on a tiltwing aircraft like that shown in FIG. 1. More specifically, by adding a second, counter-rotating blade row behind the first blade row, almost all of the swirl can be taken out of the airflow behind the propeller. This has two major effects. First, the efficiency of the counter-rotating propeller is greatly increased. The increase is roughly equal to the increase in wing cruise efficiency obtained

by turning a single-rotation propeller in a direction opposite to the wingtip vortex. In both cases the efficiency increase is due to the swirl energy, being removed, either by the rear blade row or by the wing. Second, the counter-rotating propeller imparts hardly any swirl to the flow. Therefore, the conversion envelope and the wing cruise efficiency of the vehicle are neither increased nor decreased. In sum, the use of a wingtip-mounted counter-rotating propeller increases the propeller efficiency without degrading the wing efficiency or the vehicle's conversion envelope.

By way of example, demonstrating the greatly improved efficiency obtainable because of the employment of a counter-rotating propeller rather than a single rotation propeller, a counter-rotating propeller was designed for a high speed rotorcraft military transport tiltwing. This propeller was designed to the same hover and cruise conditions as a baseline single-rotation propeller. These design conditions are shown in Table 1:

TABLE 1

Design Conditions for a high speed tiltwing aircraft		
HOVER:	Altitude	4000 ft.
	Temperature	95° F.
	Thrust <sub>hover</sub>	28,149 lb.
CRUISE:	Altitude	15,000 ft.
	V <sub>cruise</sub>	450 knots
	M <sub>cruise</sub>	0.718
	Thrust <sub>cruise</sub>	4,339 lb.
DESIGN VARIABLES HELD CONSTANT	Disk Loading	35 lb/ft <sup>2</sup>
	Solidity	0.185
	V <sub>tiphover</sub>	750 ft/sec

In addition, the solidity of the propellers, defined as:

$$\sigma = \text{Blade Area/Disk Area} \quad (1)$$

was held constant. Also, the hover tip speed was held constant at 750 ft/sec and the maximum torque of the counter-rotating propeller was limited to that of the single-rotation propeller. This allowed a true comparison between counter-rotating and single-rotation propellers. Table 2 summarizes the resulting performance of each propeller:

TABLE 2

Results of Propeller Performance Analysis		
PARAMETER	SINGLE-ROTATION	COUNTER-ROTATION
Cruise Efficiency	0.790	0.847 (+7.3%)
Maximum Torque (ft-lb)	175,644	175,644 (0.0%)
$\Delta$ Wing Efficiency	-0.204	0.0 (+26.6%)

The numbers in parentheses represent the percentage change from the single-rotation propeller. Note that the counter-rotating propeller is 0.057 (7.3%) more efficient than the single-rotation propeller. Also, the Oswald efficiency factor, defined as:

$$e = C_L^2 / C_D \pi AR \quad (2)$$

wherein  $e$  represents wing efficiency,  $C_L$  is the coefficient of lift,  $C_D$  is

the coefficient of drag, and  $AR$  is the wing aspect ratio ( $AR = B^2/S$  where  $B$  is the span and  $S$  is the wing area), is reduced by 0.204 with a single-rotation propeller but not at all (an effective 26.6% increase) by the counter-rotating propeller. This large degradation in

wing efficiency for a single-rotation propotor is due to a non-optimum span loading caused by the propotor swirl.

Referring now to FIG. 3, a graph is depicted which compares the incremental change in lift for a wing having a single-rotation propotor with that of a wing having a counter-rotating propotor, across the span of the wing. The y-axis (ordinate) represents the incremental change in lift, wherein  $C$  is the chord,  $C_{REF}$  is the reference chord, and  $C_L$  is the lift coefficient. The x-axis (abscissa) represents the position along the span of the wing, ranging from the centerline at 0.0 to the tip at 1.0. The shaded area between the dashed line (single-rotation propotor) and the solid line (counter-rotating propotor) represents the increased efficiency across the wing derivable by employing the inventive counter-rotating propotors in a typical tiltwing application. The net result, for the tiltwing aircraft utilized in this example, was a large increase in propotor cruise efficiency without the large penalty to wing efficiency associated with single-rotation propotors.

Although the inventive counter-rotating propotor disclosed in this application is especially suited for application in a tiltwing aircraft environment, it can be used with a variety of other VSTOL concepts as well. An example would be a very high-speed tiltrotor aircraft. In this case the principle application would be to eliminate the swirl component at high speed. Swirl at high speeds is detrimental to wing performance by reducing the wing's critical Mach number at which shock waves are induced on the wing's upper surface, increasing drag) due to the wing's strong sensitivity to angle of attack. Thus, using a counter-rotating propotor provides a better flow environment to the wing.

The wingtip-mounted, counter-rotating propotor concept synthesizes the best qualities of counter-rotating propellers and single-rotation propotors to provide a highly efficient cruise propulsor that offers rotor-like hover control. The use of counter-rotation allows a low to moderate disk loading propulsor to be applied to a tiltwing concept without degrading the vehicle's conversion envelope or its wing efficiency. The lower effective disk loading for the counter-rotating propotor provides a benefit in hover, since the induced power is lower than that for a single propotor of the same diameter and thrust rating. Furthermore, the wingtip-mounted counter-rotating propotor is unique in its ability to provide efficient cruise performance (both wing and propulsor) and hover control for tiltwing aircraft. Previous similar concepts were unable to synthesize the cruise performance benefits with the hover capability that is inherent in the counter-rotating propotor concept.

Although an exemplary embodiment of the invention has been shown and described, many changes, modifications, and substitutions may be made by one having ordinary skill in the art without departing from the spirit and scope of the invention. Therefore, the scope of the invention is to be limited only in accordance with the following claims.

What is claimed is:

1. An aircraft capable of in-flight conversion between a hover mode and a forward cruise mode, comprising:
  - a fuselage having a starboard side and a port side;
  - a wing section extending from each of said starboard and port sides, each said wing section being fixed in

both the hover mode and the forward cruise mode; and

at least one propotor mounted on each of said starboard and port wing sections, each said propotor comprising two blade rows positioned one behind the other along a common rotational axis, each blade row having a plurality of blades which are relatively stiff-in-plane and are mounted such that cyclic pitch adjustments may be made for hover control during flight, said two blade rows being counter-rotating;

wherein said starboard and port wing sections each have one of said propotors mounted substantially on its tip end, so that the propotor may have a relatively large diameter without impacting the fuselage; resulting in lower disk loading.

2. The aircraft as recited in claim 1, wherein said aircraft is of the tiltwing type, said wing sections tilting, in a conversion mode, from a vertical position in the hover mode to a horizontal position in the forward cruise mode, and conversely tilting, in a reconversion mode, from a horizontal position in the forward cruise mode to a vertical position in the hover mode.

3. The aircraft as recited in claim 1, wherein there is one propotor mounted on each of said starboard and port, wing sections.

4. The aircraft as recited in claim 1, wherein there are a plurality of propotors mounted on each of the starboard and port wing sections, one propotor on each wing section being mounted on the tip thereof and the remaining propotors on each wing section being mounted as closely to the wingtip as possible.

5. The aircraft as recited in claim 1, wherein each said propotor includes two rotor hubs, one of said blade rows being mounted on each said rotor hub.

6. A tiltwing aircraft capable of in-flight conversion between a hover mode and a forward cruise mode, comprising:

a fuselage having a starboard side and a port side;

a wing section extending from each of said starboard and port sides, each said wing section being fixed in both the hover mode and the forward cruise mode, and being arranged to tilt, in a conversion mode, from a vertical position in the hover mode to a horizontal position in the forward cruise mode, and conversely tilting, in a reconversion mode, from a horizontal position in the forward cruise mode to a vertical position in the hover mode; and

a propotor mounted on the tip of each of said starboard and port wing sections, said propotor comprising two blade rows positioned one behind the other along a common rotational axis, each blade row having a plurality of blades which are relatively stiff-in-plane and are mounted such that cyclic pitch adjustments may be made for hover control during flight, said two blade rows being counter-rotating.

7. The aircraft as recited in claim 6, wherein there are a plurality of propotors mounted on each of the starboard and port wing sections, one propotor on each wing section being mounted on the tip thereof and the remaining propotors on each wing section being mounted as closely to the wingtip as possible.

8. The aircraft as recited in claim 6, wherein each said propotor includes two rotor hubs, one of said blade rows being mounted on each said rotor hub.

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